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NASA/Army Rotorcraft Transmission Research, A Review of Recent Significant Accomplishments

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NASA/Army Rotorcraft Transmission Research, A Review of Recent Significant Accomplishments[1]

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ABSTRACT:

A joint helicopter transmission research program between NASA Lewis Research Center and the U.S. Army Research Lab has existed since 1970. Research goals are to reduce weight and noise while increasing life, reliability, and safety. These research goals are achieved by the NASA/Army Mechanical Systems Technology Branch through both in-house research and cooperative research projects with university and industry partners. This paper reviews some recent significant technical accomplishments produced by this cooperative research. The following research projects are reviewed: oil-off survivability of tapered roller bearings, design and evaluation of high contact ratio gearing, finite element analysis of spiral bevel gears, computer numerical control grinding of spiral bevel gears, gear dynamics code validation, computer program for life and reliability of helicopter transmissions, planetary gear train efficiency study, and the Advanced Rotorcraft Transmission (ART) program.

INTRODUCTION:

The performance of any helicopter depends greatly on the performance of the transmission. To improve helicopter performance, a joint helicopter transmission research program between the NASA Lewis Research Center and the U.S. Army Research Lab was established in 1970. Research goals have been to reduce drive system weight and noise while increasing life, reliability, and safety. These goals are achieved by the NASA/Army Mechanical Systems Technology Branch through both in-house research and cooperative research projects with university and industry partners. This paper is a review of some of the recent significant technical accomplishments produced by this research. Following are descriptions of several research projects. The projects described here are not a comprehensive list of past research activities but were selected to provide a sampling of recent research accomplishments. It is intended that this paper will provide the reader with an awareness of some recent technical advances, and it is hoped that this paper will stimulate discussions and ideas for new research topics and new cooperative efforts between the Mechanical Systems Technology Branch and others in government, academia, and industry.

RECENT TECHNICAL ADVANCES:

IMPROVED OIL-OFF SURVIVABILITY OF TAPERED ROLLER BEARINGS: The objective of this project (fig. 1) was to develop a tapered roller bearing design capable of operating for 30 min after loss of oil. Design studies of helicopter transmissions had shown that the use of tapered roller bearings on the input shaft could result in a lighter, more reliable transmission. However, the contact of the ends of the tapered rollers with the guide flange is very sensitive to proper lubrication. Therefore, the loss of oil at the conjunction can quickly lead to complete bearing failure. What was needed then was a method of providing adequate lubrication at the roller-flange interface so that the bearing could operate for at least 30 min after loss of the main oil supply.

A bearing was designed using an oil-impregnated powder metal ring for a rib (flange) with either a cup or cone design. Three materials identified in screening tests were used for the rib rings: M2 tool steel at 65 percent density and CBS 1000M steel at 65 and 75 percent density. An oil-off test was done, and it was found that the standard design bearing ran for only 10 min at 4000 rpm. On the other hand, the new survivable design with ribbed cup bearings ran for 30 min at 11 000 rpm. Another oil-off test was done at a higher speed, and the survivable design bearing operated for

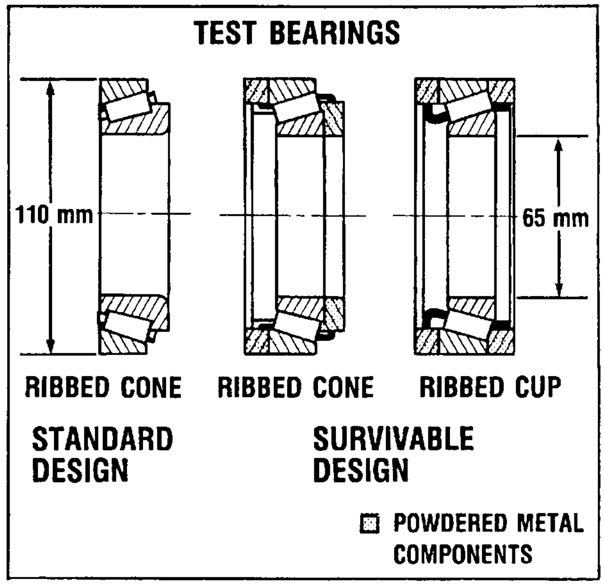
[1]*Presented at the American Helicopter Society 50th Annual Forum, Washington, DC, May 11–13, 1994.*

IMPROVED OIL-OFF SURVIVABILITY OF TAPERED ROLLER BEARINGS

MILESTONE ACHIEVED:

LABORATORY TESTS DEMONSTRATED OIL-OFF SURVIVABILITY OF TAPERED ROLLER BEARINGS TO OVER 30 MINUTES AT 11 000 RPM.

- STANDARD DESIGN RAN ONLY 10 MINUTES AT 4000 RPM.
- POWDERED METAL M-2 AND CBS 1000M STEEL AT 65 AND 75% DENSITY USED FOR RIB RINGS.
- NASA CR-180804 AVSCOM TR-87-C-29



SIGNIFICANCE:

TAPERED ROLLER BEARINGS CAN NOW BE CONSIDERED FOR USE IN ADVANCED DESIGN HELICOPTER TRANSMISSIONS TO REDUCE WEIGHT AND INCREASE LIFE.

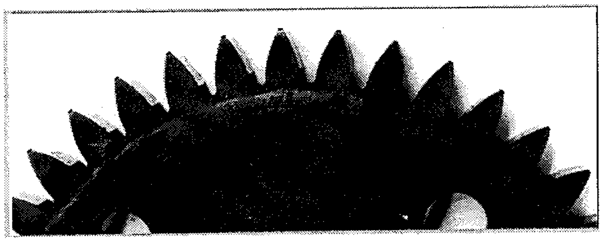
Figure 1.—Improved tapered roller bearings.

less than 5 min at 17 000 rpm. Further details of this project are available in NASA CR–180804 (ref. 1). The improved design extends oil-off operation of tapered roller bearings to over 30 min at 11 000 rpm (0.7 million DN) at typical helicopter transmission loads, thus permitting consideration of tapered roller bearings on the input shaft and enabling a lighter, more reliable helicopter transmission.

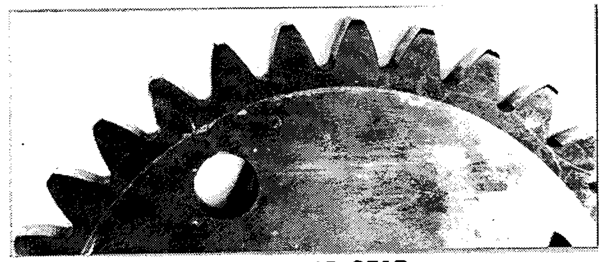
DESIGN AND EVALUATION OF HIGH CONTACT RATIO GEARING: The objective of this project (fig. 2) was to improve the surface fatigue life, scoring load capacity, and power-to-weight ratio of helicopter transmission gears by using a high contact ratio gear design. A high contact ratio design is one concept for improving the performance of spur gears that had not been fully explored. Standard low contact ratio spur gearing is designed to operate at contact ratios between 1.4 and 1.6, where contact ratio is defined as the average number of tooth pairs in contact as the gears rotate. Thus, a typical contact ratio of 1.5 means that two tooth pairs are in contact half the time and only one tooth pair is in contact the other half. High contact ratio gearing (HCRG) is defined as having at least two tooth pairs in contact at all times, i.e., contact ratios of 2.0 or more. Because the transmitted load is shared by at least two pairs of teeth, the individual tooth loading is less for HCRG than for low contact ratio designs, thereby enabling a higher power-to-weight ratio. HCRG, however requires gear teeth with lower pressure angles, finer pitches, or increased working depths; all of which tend to increase the tooth bending stress. In addition, it was expected that HCRG would be more sensitive to tooth spacing errors and profile modifications because of the simultaneous tooth contacts. The basic problem to be resolved was whether the lower tooth loads occurring in the high contact ratio design configuration more than offset the effects of the weakened tooth form, especially when run under dynamic load conditions.

A contract was established with Sikorsky Aircraft to design and experimentally test high contact ratio gears in comparison with standard low contact ratio gears. Designs were analyzed using computer program GRDYN (Gear Dynamic Analysis) (ref. 2) to simulate gear dynamic behavior. Results of the gear dynamic simulation study enabled the selection of an optimum tooth profile for minimum dynamic load. The profile selected had a quadratic tooth profile modification, beginning at 90 percent of the tooth addendum and ending with the maximum modification at the tip of the tooth.

HIGH CONTACT RATIO GEARING-DESIGN AND EVALUATION



HIGH CONTACT RATIO GEAR



STANDARD GEAR

MILESTONES ACHIEVED:

- COMPLETED DESIGN AND ANALYSIS
- COMPLETED FATIGUE AND LOAD CAPACITY EXPERIMENTS
- DEFINED OPTIMUM TOOTH SHAPE USING COMPUTER SIMULATION
- NASA CR 174958 PUBLISHED

SIGNIFICANCE:

- HIGH CONTACT RATIO GEARS HAVE TWICE THE LIFE OF STANDARD GEARS
- HIGHER LOAD CAPACITY
- INCREASED LIFE, RELIABILITY, AND POWER-TO-WEIGHT RATIO FOR HELICOPTER DRIVE SYSTEMS

Figure 2.—High contact ratio gearing.

Fourteen standard and fourteen high contact ratio gears were fabricated and tested in a four-square (power recirculating) test rig to determine the relative fatigue lives. The failure distributions of the gears was established for a specific load of 6667 lb/in. of tooth face-width. The HCRG had two times the fatigue life of standard gears at the 10 percent failure point. The load capacity for resistance to scuffing/scoring was also determined. The HCR gears carried 5600 lb/in. with a 50 percent scuffing/scoring occurrence, which is slightly better than the 4500 lb/in. carried by standard gears.

During the study it was found that computer program GRDYN was essential to establishing a viable design of the high contact ratio gear. The reason was that high contact ratio gears are very sensitive to the effects of tooth profile modifications on the load sharing and resultant dynamic loads. Further details are reported in NASA CR–174958 (ref. 3).

The results of this research project show that gear fatigue life can be doubled by using high contact ratio gears instead of standard gears and that high contact ratios gears have slightly better load capacity compared to standard gears when the mode of failure is scoring (scuffing). Therefore, high contact ratio gears can significantly increase life, reliability, and power-to-weight ratio for helicopter transmissions.

FINITE ELEMENT ANALYSIS OF SPIRAL BEVEL GEARS: The objectives of this project (fig. 3) were: (1) to develop a computer code for calculating the true surface coordinates of spiral bevel gear teeth based on the manufacturing conditions and (2) to demonstrate the new code's use in conjunction with modern finite element analysis tools.

Spiral bevel gears are used in helicopters to transfer power from the horizontal axis engines to the vertical axis main rotor shaft. Fast, accurate finite element analysis methods are needed to improve the power transfer and minimize the weight for helicopter drive systems.

The finite element technique has been successfully applied to parallel axis gears. For these gears, the well-known involute function provides a closed-form equation that can be used to solve for the tooth surface coordinates. However, there is no closed form equation for the tooth surface coordinates of spiral bevel gears, and because their geometry is so complicated,

until now only approximations of the tooth surface could be used in an analysis. A method to more accurately define spiral bevel gear tooth surface coordinates was needed and has been developed. The method simulates the manufacturing process numerically with a set of simultaneous nonlinear algebraic equations based on the gear geometry theory developed by Litvin at the University of Illinois at Chicago (ref. 4).

A computer program, SURFACE, has been written. Inputs to the program are the manufacturing machine tool settings and the basic gear design variables. The output is the set of coordinates forming a surface grid for both sides of the gear tooth. Once the tooth surface coordinates are determined, computer programs PATRAN and MSC/NASTRAN can be used for the structural analysis. The surface grid calculated by SURFACE is input to the modeling program PATRAN permitting a one-tooth model to be produced. Within PATRAN the desired number of teeth can be generated and the applied load and boundary conditions defined. PATRAN then provides input to MSC/NASTRAN for the structural analysis for the spiral bevel gears. The major principle stresses are calculated by MSC/NASTRAN and displayed by PATRAN. Further details are reported in NASA TP–3096 (ref. 5).

Computer program SURFACE permits rapid, accurate model development for finite element analysis of spiral bevel gears. This will enable the design of lighter, more reliable gears for rotorcraft applications.

COMPUTER NUMERICAL CONTROL GRINDING OF SPIRAL BEVEL GEARS: The objective of this project (fig. 4) was to develop a grinding process for spiral bevel gears that would lower component costs by: (1) reducing the time required for machine setup and maintenance of the setup by 50 percent and (2) improving the machine repeatability.

The aerospace gear manufacturing community is typically faced with many problems when producing aircraft quality spiral bevel gears on manually controlled manufacturing machines. Manually controlled bevel gear grinding machines require manual adjustment for all process variables. Long setup times are common when changing the machine over to manufacture a different gear. Also, due to the extremely tight tolerances on the manufactured components, machine adjustments are necessary after every few parts to keep the finished product within tolerance. These adjustments require the continuous attendance of a highly skilled operator. Another problem peculiar

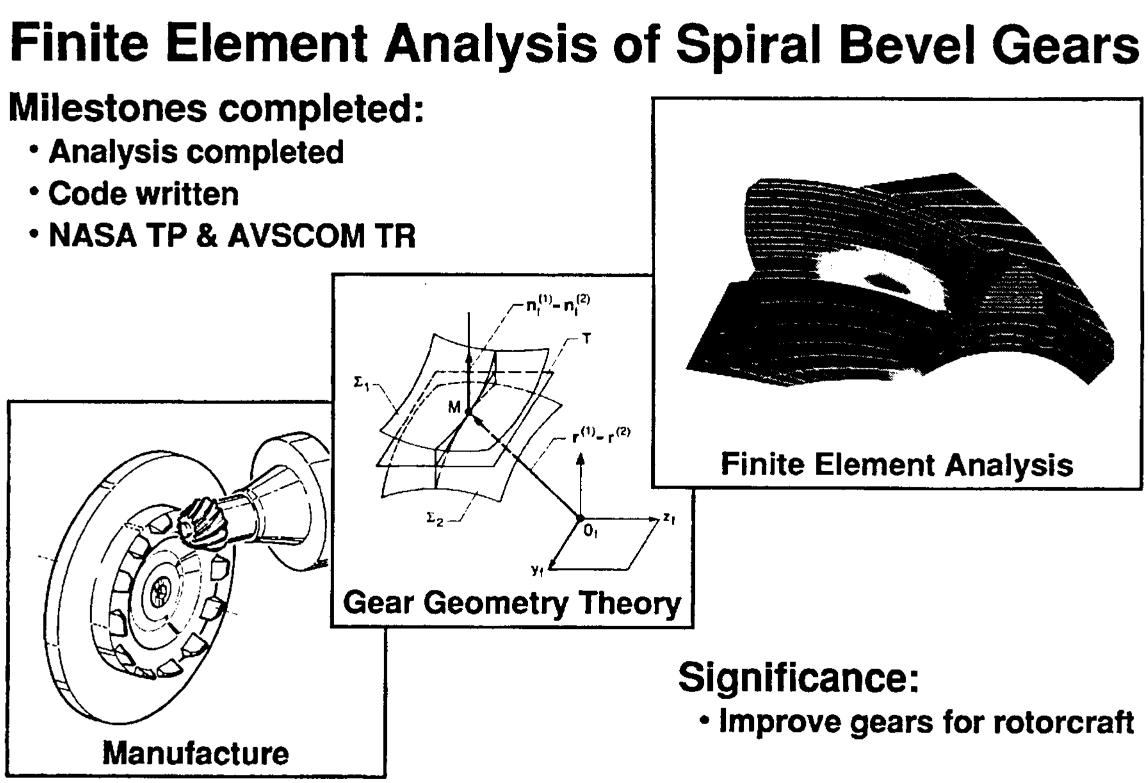


Figure 3.—Spiral bevel gear analysis.

to the aerospace gearing community is the small number of components, typically 20 gears or less, that are in a given production run. In small runs, the setup costs have a large influence on the total cost of each part.

The U.S. Army determined it would be in their best interest to improve the state of the art in spiral bevel gear grinding through their Manufacturing Methods and Technology (MM&T) activity. The approach of the project was to convert a manually controlled Gleason Gear Grinder to a computer numerical controlled (CNC) grinder. A contract was established with Bell Helicopter Textron Inc. The Gleason Works was a major subcontractor with responsibility for the design, building, and acceptance testing of the prototype machine. Bell Helicopter then tested the prototype machine in a production environment.

The program was completed in three phases: Phase I involved the design of the prototype CNC grinder based on the model 463 Gleason manual grinder. A large number of the manual setup variables were eliminated. Where manual settings were still required, electronic positioning systems were used to prevent operator errors. A CNC controller was added to monitor and control the manufacturing process. Phase II entailed taking a U.S. Army owned manual grinder, having it rebuilt, and adding the CNC machine improvements. Phase III was for production testing of the prototype machine. The machine was sent to Bell Helicopter and installed in their gear production plant in Fort Worth, Texas. The machine was used to support their production requirements and conduct tests on a wide size range of gears. Improvement of the spiral bevel gear grinding process due to the addition of CNC was then measured through time-study of machine setup and production.

Two major machine improvements were made. A CNC dresser system was added to accurately control grinding wheel shape. Also, the drive system that controls the motion between the cradle and work piece was radically altered. On the manual machine this motion was controlled through a cam, shafts, and gears. The new design eliminated many of these. The drive system now has a minimum of gear sets and position is controlled via optical encoders. Also, software for CNC control of machine processes and spiral bevel gear manufacturing methodologies was developed. A series of nine tests were used to assess the improvements due to the addition of CNC. Over the nine tests the average savings on setup and maintenance of setup time was 65 percent. This means

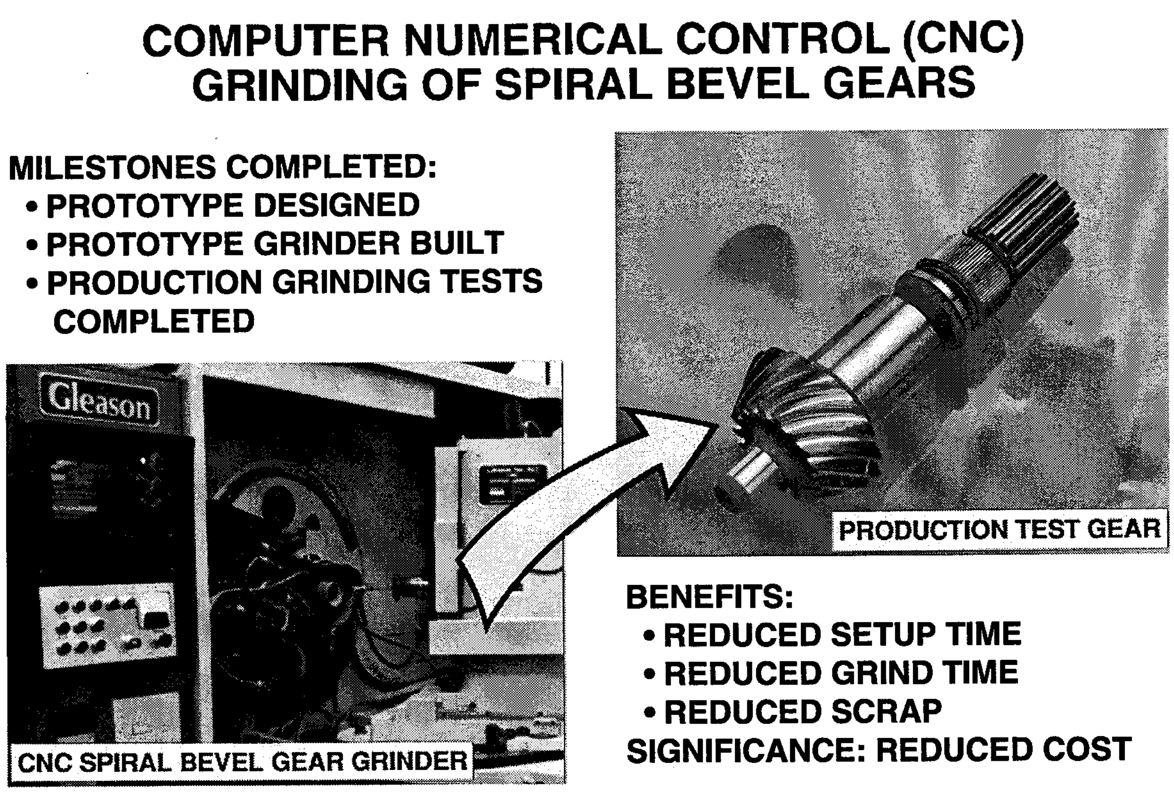


Figure 4.—Spiral bevel gear grinding.

reducing the setup time that currently takes over 32 hr down to just over 11 hr. The average savings in grind cycle time (time spent grinding) was 34 percent. This savings demonstrates increased material removal rate which was made possible by a stiffer grinding wheel support structure. Further details are reported in NASA CR–187175 (ref. 6).

CNC conversion of existing manual machines can provide many benefits to the aerospace gear manufacturing community. Many of the process variables are now easier to control. Resetting of the machine for a new job has a much lower time to production. All are benefits in reducing production costs for aerospace spiral bevel gears.

GEAR DYNAMICS CODE VALIDATION: The objective of this project (fig. 5) was to validate a gear dynamics computer code through experiments. The major source of helicopter cabin noise is attributed to vibration generated by the numerous gear meshes within the gearbox and transmitted to the airframe. Noise levels in excess of 100 dB have been measured. This leads to pilot fatigue, disrupted communications, and unhealthy conditions for both crew and passengers. If helicopter transportation is to flourish in the civil transport markets, the cabin noise level must be drastically reduced.

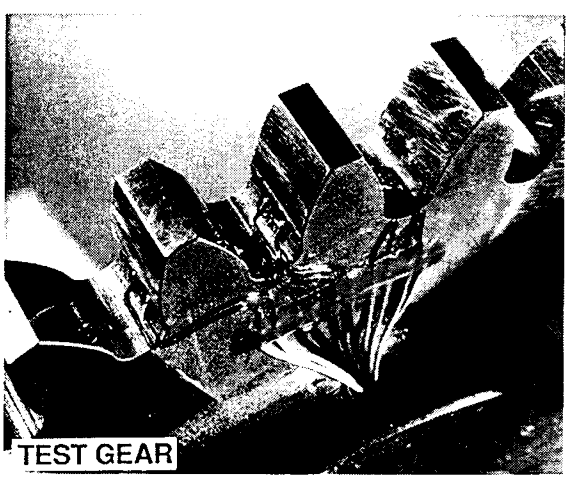
Gear vibration and gear noise is primarily caused by the abrupt transition of the load from tooth to tooth as the gears rotate. Modifications to the profile of gear teeth are often used to help smooth this dynamic action. The effects of tooth profile modification on gear dynamics is simulated by several computer codes developed through NASA grants and contracts. The gear dynamics codes can predict the loads on a gear tooth under a static condition as well as at typical operating speeds where the interaction of system mass and stiffness properties produces dynamic effects. As the gears rotate, the point of contact between the teeth moves along the profiles of the teeth. As this happens the magnitude of the contact force varies as a function of the rotational speed. There has been an acute need to verify these codes with experimental data taken under carefully controlled conditions. The specific goal of this project was to verify predictions of the gear dynamics code DANST (Dynamic ANalysis of Spur gear Transmissions) (ref. 7) for both gear tooth loads and for the bending stress at the gear tooth root.

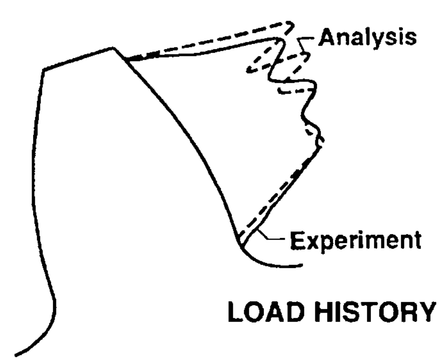
Gear dynamics experiments were conducted in the Gear Noise Facility at NASA Lewis. An instrumented gearbox was tested over a range of speeds and loads to obtain experimental data for comparison with the results of the DANST code. Test instrumentation

GEAR DYNAMICS CODE VALIDATION

MILESTONES COMPLETED:

- **Compared analysis and experiment**
- **28 test conditions**
- **Successfully predicts dynamic loads**
- **NASA TM 103232**





SIGNIFICANCE:

- **Experimental verification of gear dynamics code**
- **Allows tuning gear profile for minimum noise and vibration**

Figure 5.—Gear dynamics code validation.

included miniature strain gages installed in gear tooth roots, rotary accelerometers mounted on the gears, accelerometers mounted on the gearbox case and on the bearing mounts, and load cells mounted under the gearbox supports. Primary emphasis to date has been on gear tooth strain gage data which provide information on tooth bending stresses and on tooth-to-tooth loads.

Tests have been completed on a pair of standard involute spur gears with a linear profile modification. The test gear data are as follows: 28 teeth, 8 diametral pitch, 3.5 in. pitch diameter, and 0.25 in. face width. The 28 test conditions included speeds from 800 to 6000 rpm and torques from 16 to 110 percent of the gear design torque. The experimental data were compared to analyses, and in all cases the waveforms are similar. This indicates that the analysis does simulate the physical behavior of the test gears. Also, the analysis successfully predicts loss of tooth contact that occurs when the gears are run at high speeds and with a light load.

The experimental peak value of the dynamic load was also compared with DANST predictions for all test conditions. The maximum dynamic load prediction generally agreed with measured results within 6 percent. Strain gages were used to also measure the bending stress at the tooth root for comparison with DANST predictions. The analysis generally agreed with measured results for the tooth root location within 10 to 15 percent. Further details are reported in NASA TM–105362 (ref. 8). The validated code will allow a gear designer to tune the profile of a new gear to minimize dynamic loads and stress with the potential to reduce noise and vibration without expensive and time-consuming hardware testing. The code will also predict the effects of load and speed on the dynamics of a gear system.

COMPUTER PROGRAM FOR LIFE AND RELIABILITY OF HELICOPTER TRANSMISSIONS: The objectives of this project (fig. 6) were to create analytical tools for predicting helicopter transmission life and reliability, to examine the design and operating parameters that affect transmission life, and, thereby, to increase the actual life and reliability for helicopter transmissions.

Life and reliability are important issues during the design, development, and field operation of helicopter transmissions. Light weight and high power capacity

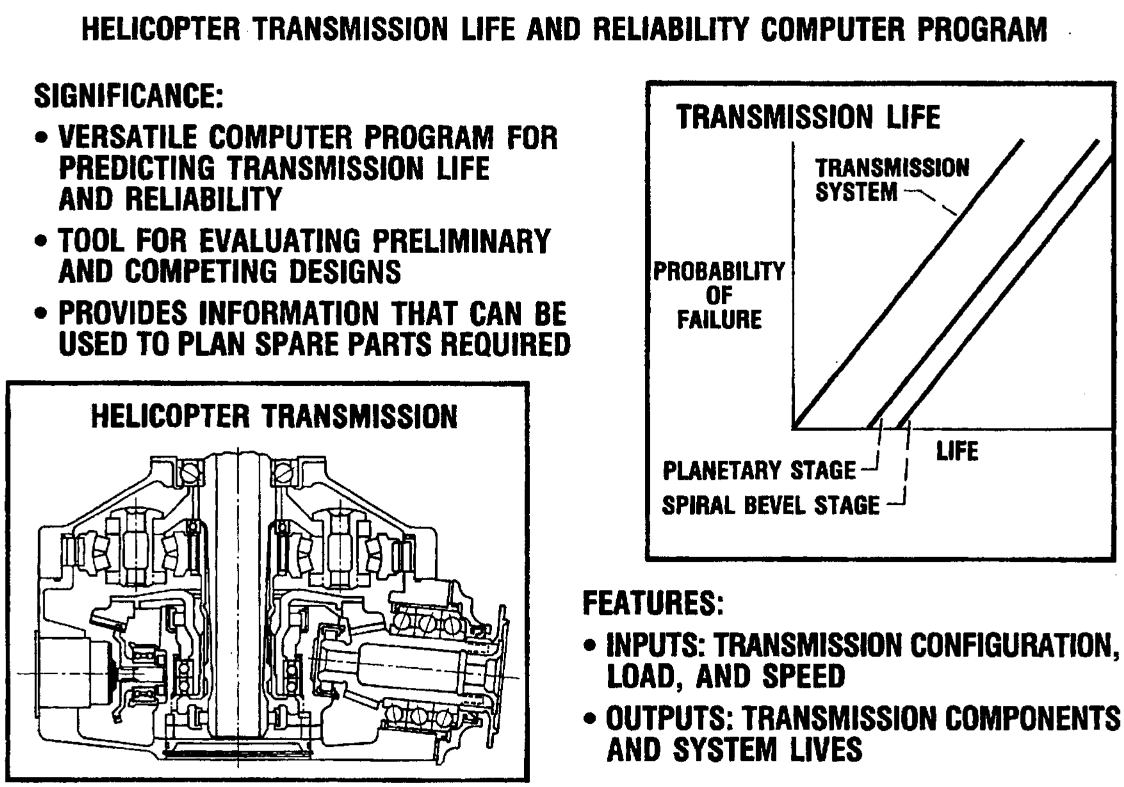


Figure 6.—Helicopter transmission life and reliability.

must be balanced with requirements for long life and low maintenance costs. In the past, analytical tools for predicting transmission life were not available. They are needed for design and for comparing competing and alternate designs.

Bearing and gear lives are major factors in determining total transmission system lives. Even under ideal conditions of proper design, lubrication, and operation, bearings and gears will eventually fail by the pitting fatigue mode of failure. Pitting fatigue is the expected failure mode because there is no material endurance limit for bearings or gears.

Analytical models and computer programs for gear and bearing life have already been developed under NASA/Army sponsorship. Previous analytical studies were successful in applying those models to transmissions. The work was laborious and only several transmissions were studied, the results being published in several NASA reports. A need was perceived then for a more general computerized model capable of efficient analysis for a large variety of different transmission designs. A computer code of this type makes it possible to evaluate the life and reliability of proposed transmission designs, optimize those designs, and predict spare parts required over the useful life of the helicopter fleet.

A computer program was developed to predict helicopter transmission life. The program can analyze a variety of configurations composed of spiral bevel gear meshes and planetary gear meshes. Spiral bevel reductions may have single or dual input pinions and gear shafts can be straddle mounted or overhung on the support bearings. The planetary reduction has the sun gear as input, the planet carrier as output, and the ring gear fixed. The planet gears may be plain or stepped and the number of planets may vary.

The program determines the forces on each bearing and gear for a given transmission configuration and loading. The life of each bearing and gear is determined using the fatigue life model appropriate to that component. The transmission system life is determined from the component lives using rigorous methods of probability and statistics. The transmission life at a given reliability can then be found. Program output consists of component and total system lives and dynamic capacities. Further details are reported in NASA CR–3967 (ref. 9). The computer program is a valuable tool for evaluating preliminary designs and comparing competing and alternate designs. From the life predictions, the mean time between failures can now be calculated using rigorous statistical methods.

PLANETARY GEAR TRAIN EFFICIENCY STUDY: The objective of this project (fig. 7) was to experimentally test a transmission planetary gear stage over a wide variety of operating conditions and compare measured efficiency to computer predicted values.

Helicopter transmissions are very efficient. Depending on operating parameters such as speed, load, and temperature, the efficiency of the complete helicopter transmission is typically above 97 percent. However, even a slight improvement in efficiency can have an effect on the complete transmission system. Changes in operating parameters, such as reduced volume of lubricant or increased lubricant temperature, may yield only a small improvement in efficiency, but offer multiple benefits in the reduced size/weight of the oil cooler and reduced vulnerability.

Helicopter transmission efficiency is usually determined by testing the complete transmission. However, in this type of testing it is difficult to distinguish the effects of individual components on transmission efficiency. Isolation of individual components, such as the planetary gear train, allows direct control of operating conditions and permits a wide range of test parameters.

A parametric study was performed on a helicopter transmission planetary stage having a four-planet configuration. Two planetary stages were driven in a back-to-back, test/slave arrangement. A total of 130 different conditions were tested. Test parameters included sun-gear speeds to 1622 rpm and input torque to 1840 N*m (16 300 in*lb). Two different gear lubricants were used, flow rates were varied, and oil inlet temperature was changed to experimentally measure the effect of these parameters. Experimentally measured efficiency over all the test variables ranged from 99.44 to 99.75 percent.

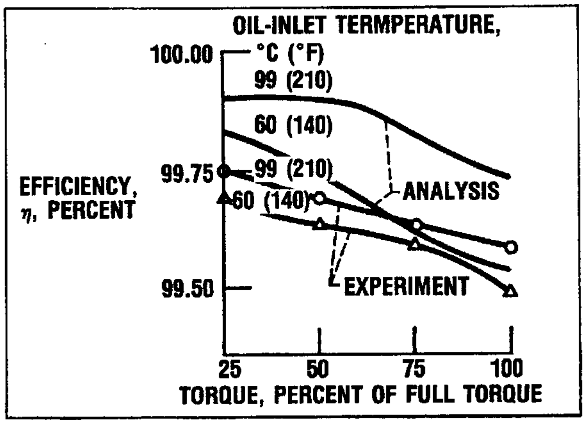
Analytical performance predictions were made and compared to measured results. The analytical results were obtained by modeling the test hardware and operating conditions. Computer programs that predict power loss for external gears, internal gears, and the planetary bearings were used. Generally, the trends in efficiency with parametric variations were similar for the analysis and experiment, but the analytical results predicted higher efficiencies than were experimentally measured. The difference between the experimental and analytical results is believed to be due to gear pumping losses that are not accounted for in the analytical model. It is now suspected that the gear

PLANETARY GEAR TRAIN EFFICIENCY STUDY

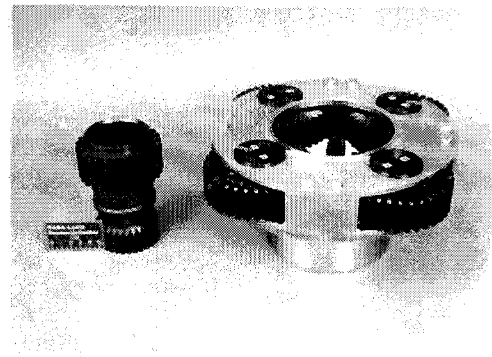
MILESTONES COMPLETED:

- PARAMETRIC STUDY COMPLETED
- ANALYTICAL AND EXPERIMENTAL RESULTS COMPARED
- NASA TP-2795

EFFICIENCY RESULTS



PLANETARY TEST HARDWARE



SIGNIFICANCE:

- ANALYTICAL AND EXPERIMENTAL RESULTS FOLLOWED SIMILAR TRENDS
- SENSITIVITY OF PLANETARY PERFORMANCE TO TEST PARAMETERS MEASURED

Figure 7.—Planetary gear train efficiency study.

pumping loss, which was previously believed to be negligible, is important in jet lubricated gear meshes operating at low speeds as the planetary gears did in this experimental study. Further details are reported in NASA TP–2795 (ref.10). The computer code is partially validated, but it must be improved by adding methods to incorporate gear pumping losses.

ADVANCED ROTORCRAFT TRANSMISSION PROGRAM: The objective of this project is to identify key component and subsystem technologies to attain the weight, noise, and life goals of the advanced rotorcraft transmission program. The specific drivetrain goals are: (1) a 25-percent reduction in weight; (2) a 10-dB reduction in noise, and (3) a 5000-hr mean time between removal (MTBR). Historically, technology advancements in airframes, rotors, and engines have been continuously integrated into rotorcraft. The integration of advances in drivetrain technology, however, has been lagging. In general, advancements resulted only in areas where problems occurred. Thus, three major shortcomings exist today in rotorcraft drivetrains: excessive weight, excessive noise generation, and short life. The Advanced Rotorcraft Transmission (ART) Program was initiated to meet and overcome these shortcomings.

The ART program is an Army-funded, joint Army/NASA program. Its intent is to develop and demonstrate lightweight, quiet, durable drivetrain systems for next generation rotorcraft. The four major contract participants in ART are: McDonnell Douglas Helicopter Company, Boeing Helicopters, Bell Helicopter Textron, and Sikorsky Aircraft. NASA Lewis is also providing in-house technical support and testing. ART addresses the general requirements of two distinct next-generation aircraft classes: (1) Future Air Attack Vehicle, a 10 000 to 20 000 lb aircraft capable of undertaking tactical support and air-to-air missions; and (2) Advanced Cargo Aircraft, a 60 000 to 80 000 lb aircraft capable of heavy lift field support operations.

The technical approach toward achieving the ART goals includes use of new ideas in gear configuration, transmission concepts, and airframe/drivetrain integration. Also included is the application of the latest available component, material, and lubrication technologies. All four contracts have the same format and contents. The tasks of the contracts are:

Task 1: Establish a baseline aircraft and transmission

Task 2: Perform transmission configuration studies and choose the most promising configuration
Task 3: Perform mission studies to determine the effect of the advanced transmission on the aircraft
Task 4: Identify and design critical components required for the advanced transmission
Task 5: Develop a component test plan
Task 6: Fabricate the test rigs
Task 7: Fabricate the test specimens
Task 8: Test the components

In addition, in-house technical support is also being provided at NASA Lewis. Cooperative projects between NASA Lewis and the contractors have been established. McDonnell Douglas, Boeing, and Bell will provide hardware to test in the unique NASA Lewis facilities.

Candidate drivetrain systems have been carried to a conceptual design stage. Tradeoff studies have been conducted resulting in selection of the ART transmission for each contractor. The selections were based on comparative weight, noise, and reliability studies. Preliminary designs of each ART transmission have been completed, as have mission impact studies. Comparisons of aircraft mission performance and life cycle costs were undertaken for the next-generation aircraft with ART and with the baseline transmission. From these studies, new and critical component technologies for the ART transmissions were identified.

The results obtained from completion of the first five contract tasks for each of the four major contractors are presented in the paragraphs that follow.

BELL HELICOPTER TEXTRON INC. ADVANCED ROTORCRAFT TRANSMISSION PROJECT: Bell Helicopter selected for their application the Future Air Attack Vehicle (FAAV). They defined as their baseline a tiltrotor aircraft and chose a high contact ratio planetary stage as their advanced technology configuration.

Based on the trade studies, preliminary design, and life cycle cost evaluation, the chosen configuration can meet the three main goals of the project while lowering the life cycle cost of a fleet of aircraft that is based on the chosen FAAV. A 31 percent reduction in weight has been attained. Also, a 6 to 10 dB reduction in source noise and a MTBR well in excess of 5000 hr have been predicted for the ART transmission. A $333M life cycle cost savings for the aircraft fleet is estimated due to the ART program research.
Bell Helicopter is concentrating its component test program (fig. 8) in three major areas: planetary gear train tests, material tests, and spiral bevel gear tests. The planetary gear train will be tested for noise/vibration, efficiency, fatigue, and loss of lubricant. Material testing will be done in coupon and full-scale hardware. X-53 gear steel will be extensively studied to assess heat treatment effects on bending fatigue. Investment cast titanium housing and planetary carrier will be assessed in conjunction with other component tests. High temperature magnesium will be tested and compared to current magnesium transmission housings for creep and corrosion. NASA Lewis and Bell established a joint project to test spiral bevel gears in the NASA 500-hp Test Stand. Spiral bevel gears will be tested to verify reduced noise and improved strength through changes in fillet/root design and gear tooth surface geometry. Strain gage surveys will determine bending stress reduction and noise/vibration tests will assess tooth geometry changes. Pitting, bending, and scoring tests will be conducted by Bell to verify component durability. Further details are available in AIAA 92-3366 (ref. 11).

BOEING HELICOPTERS ADVANCED ROTORCRAFT TRANSMISSION PROJECT: Boeing Helicopters selected for their application the Future Air Attack Vehicle (FAAV). They defined their baseline as a tiltrotor aircraft and chose a helical three-stage planetary as their advanced technology configuration.

Based on the preliminary design and tradeoff studies, the ART program goals of weight, noise, and reliability are attainable. The 443 lb (24.6 percent) drivetrain weight reduction enables a 946 lb (5.5 percent) reduction in the aircraft's takeoff gross weight. For a fleet of 400 aircraft a $116M cost savings is estimated due to the ART program research.

The testing planned by Boeing Helicopters (fig. 9) also contains generic material testing and specific design-related component testing. Gears made from Vasco X–2 high-temperature material and manufactured using near-net-shape forging will be tested. Lightweight accessory drive gears made from titanium with treated surfaces are also planned for testing. High-contact-ratio (HCR) gears which allow improved tooth load sharing for weight and noise reductions are to be tested. Boeing, jointly with NASA Lewis in the NASA Gear Noise Test Rig, will also be evaluating noise generation properties of eight parallel axis gear

BELL HELICOPTER TEXTRON INC. ART PROGRAM

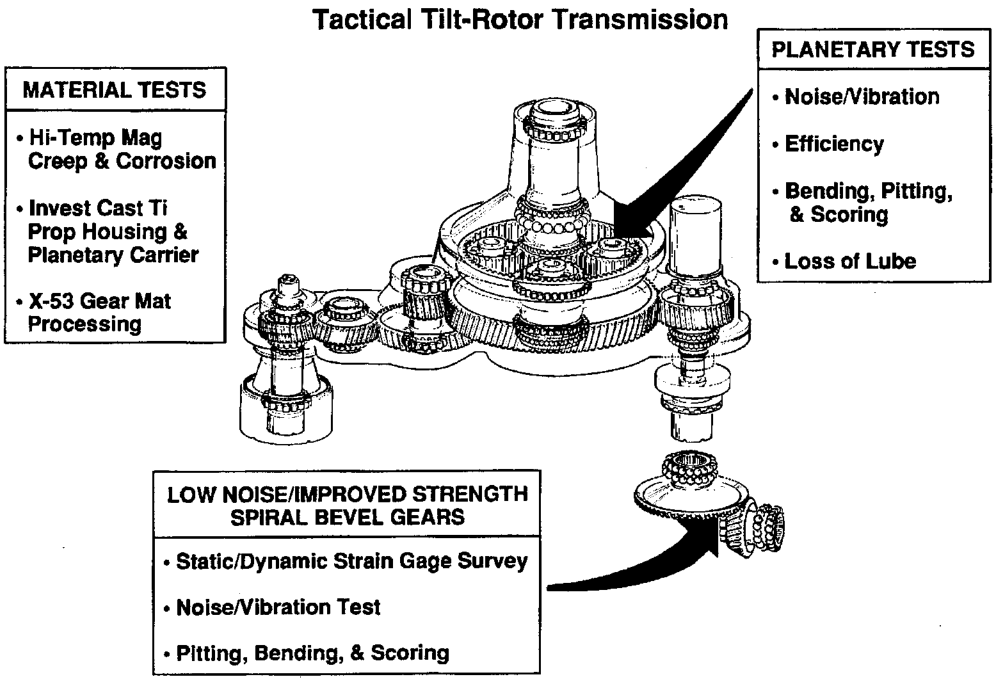


Figure 8.—Bell Helicopter ART program component test plan.

BOEING HELICOPTERS ART PROGRAM

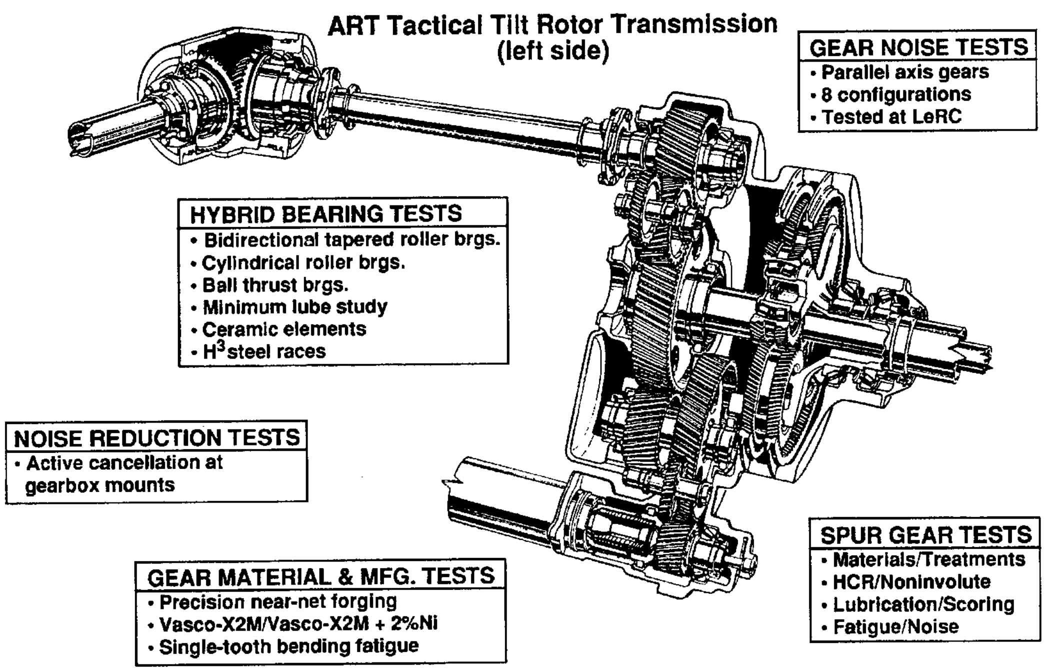


Figure 9.—Boeing Helicopter ART program component test plan.

configurations. These include various HCR, noninvolute, helical, and double-helical gear types. Application of active force cancellation at the transmission mounts for noise control is being evaluated and will be tested on full-scale CH–47D transmission hardware at Boeing. Boeing has a substantial effort planned for hybrid bearing testing. Hybrid bidirectional tapered roller bearings are a key feature of their ART gearbox design. Cylindrical and ball-thrust hybrid bearings are also planned for testing. The hybrid bearing technology is aimed at allowing higher operating temperatures and producing greater reliability. By operating at higher temperatures, oil cooler system size can be reduced to save weight. Further details are reported in NASA TM–104474 (ref. 14).

McDONNELL DOUGLAS HELICOPTER COMPANY ADVANCED ROTORCRAFT TRANSMISSION PROJECT: McDonnell Douglas Helicopter Company (MDHC) selected for their application the Future Air Attack Vehicle (FAAV). They defined their baseline as an upgraded AH–64 Apache helicopter and chose a split-torque transmission with face gears as their advanced technology configuration.

Based on the preliminary design and tradeoff studies, the ART program goals of weight, noise, and reliability are attainable. The split-torque transmission configuration with face gearing offers a large weight reduction benefit. The transmission weight reduction and life goals influence a significant cost savings in transmission acquisition and operating costs. For a fleet of 600 aircraft flying 25 years at 420 flight hours per year, a $420M life cycle cost savings is estimated due to the ART program research.

The testing planned in support of the ART program (fig. 10) varies from generic material testing to specific design-related component testing. MDHC plans to perform single tooth bending tests, gear scoring tests, impact toughness tests, and fracture toughness tests for a variety of advanced materials. The gear materials are for next-generation gearboxes and are high-temperature, high-strength steels (M50NiL, CBS 600, Maraging 300, and X–53). These materials will be compared to the baseline 9310 steel. All test specimens will be manufactured using advanced near-net-shape gear forging for improved strength and reduced manufacturing costs. MDHC also plans to perform basic tests on advanced magnesium and aluminum housing materials. Related to specific design concepts, MDHC plans on validation tests for face gears. Face gears were chosen by MDHC in the ART configuration as an alternative to spiral bevel gears. Face gears,

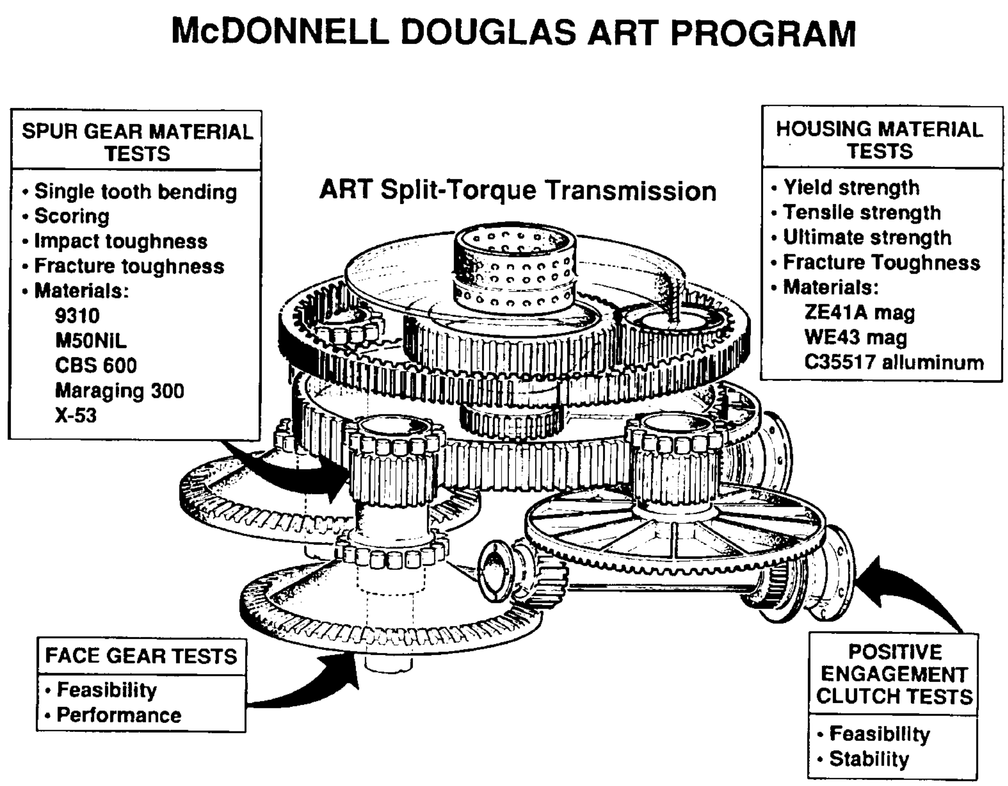


Figure 10.—McDonnell Douglas ART program component test plan.

however, have not yet been demonstrated in high-speed, high-load rotorcraft drivetrain applications. NASA Lewis and MDHC established a joint project to test face gears in the NASA Spiral Bevel Rig. Further details are reported in AIAA 92–3363 (ref. 13).

SIKORSKY AIRCRAFT ADVANCED ROTORCRAFT TRANSMISSION PROJECT: Sikorsky Aircraft selected for their application the Advanced Cargo Aircraft (ACA). They defined as their baseline an upgraded CH–53 helicopter and chose a three-stage 11:1 ratio split torque as their advanced technology configuration. The preliminary design along with the trade studies completed indicate that all ART program goals as they pertain to the Advanced Cargo Aircraft are attainable. The life cycle cost savings attributed to ART, assuming a fleet of 600 aircraft, a 240 flight hour utilization over a 35-year life cycle period, is estimated to be $1.7 billion. Sixty-five percent of the savings is in operating costs and 35 percent in acquisition costs. A major portion of the component validation planned by Sikorsky Aircraft (fig. 11) will be performed utilizing a scaled-down version (one-half size) of the split-path transmission configuration proposed for the Advanced Cargo Aircraft. Included in the testing are the following: high-contact-ratio double-helical gears on the output stage, double-helical pinions with large gear tooth face width-to-diameter ratios, an elastomeric torque-sharing device, topological gear tooth profiling for improved load distribution, high-temperature operation (300 °F), and scoring resistant X–53 gear material. Transmission error measurements will also be made. Each of the above items contribute to attaining the stated goals of the program. A separate bearing test will validate the performance of a hybrid angular contact/spherical roller bearing. The bearing has ceramic rolling elements, X–53 races, and silver-plated steel cages. The tests will consist of various thrust and radial loads, speeds up to 14 000 rpm, and loss of lubrication. In addition, extensive use of weight-saving composite materials are being investigated for future testing. The applications are for the gearbox housing, main rotor quill shaft, engine input quill shafts, and the main rotor truss. Further details are reported in NASA TM–105665 (ref. 11).

CONCLUDING REMARKS

The purpose of this report has been to review some recent and significant technical advances resulting from the NASA/Army helicopter transmission research program. The goals of the research program have been to reduce drive system weight and noise

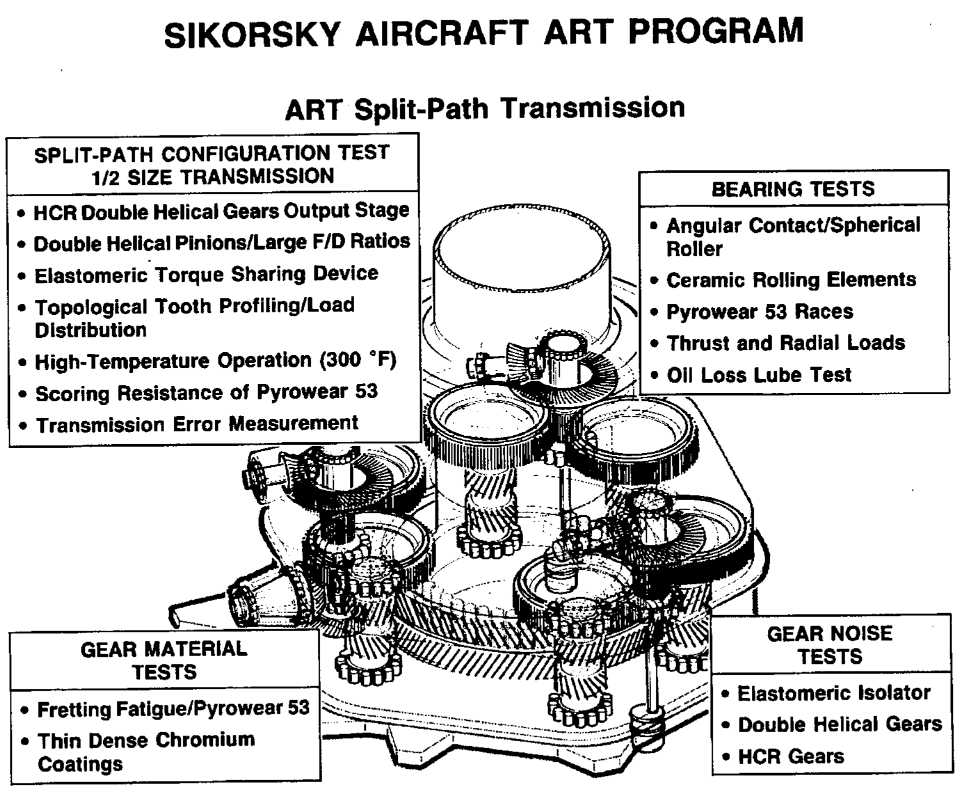


Figure 11.—Sikorsky Aircraft ART program component test plan.

while increasing life, reliability, and safety. These goals are achieved through in-house research of the NASA/Army Mechanical Systems Technology Branch and through cooperative research among NASA, Army, university, and industry partners. The research projects described here have produced technical advances that have supported the research program goals. It is hoped that this paper has provided the reader with an awareness of some recent technical advances and that this paper will stimulate discussions and ideas for new research topics and new cooperative efforts between the Mechanical Systems Technology Branch and others in government, academia, and industry.

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13. ABSTRACT ***(Maximum 200 words)***

A joint helicopter transmission research program between NASA Lewis Research Center and the U.S. Army Research Lab has existed since 1970. Research goals are to reduce weight and noise while increasing life, reliability, and safety. These research goals are achieved by the NASA/Army Mechanical Systems Technology Branch through both in-house research and cooperative research projects with university and industry partners. This paper reviews some recent significant technical accomplishments produced by this cooperative research. The following research projects are reviewed: oil-off survivability of tapered roller bearings, design and evaluation of high contact ratio gearing, finite element analysis of spiral bevel gears, computer numerical control grinding of spiral bevel gears, gear dynamics code validation, computer program for life and reliability of helicopter transmissions, planetary gear train efficiency study, and the Advanced Rotorcraft Transmission (ART) program.

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